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Analysis and co-ordination of the activities concerning gasification of biomass

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Country Report, Denmark and Norway

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Abstract. This report, which is a part of the European Union Concerted action project "Analysis and Co-ordination of the Activities Concerning a Gasification of Biomass" (AIR3-CT94-2284) describe the background and the status of the biomass gasification activities in Denmark and to some extent also the Norwegian activities.

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1. General information on national energy systems

1.1. Denmark

1.1.1. Primary energy consumption

The total Danish consumption of primary energy is around 800 PJ/year including the transport sector.

Nuclear power was intensively discussed but never realised in Denmark, which has essentially no hydropower resources either. Therefore when Denmark stopped its massive use of oil in the years after the oil crises, imported coal has been and still is the dominating fuel for electricity production (approx. 67 % according to Danish Energy Statistics, 1995).

As a consequence of the national CO_2 policy, the power utility sector to some extent will shift from coal to natural gas and biomass. Hence, a number of de-central Combined Heat and Power (CHP) Plants and some large-scale central plants have turned to or have been constructed for natural gas; e.g. all tree older power plants in the capital area have been converted to natural gas and one new 400 MW_e natural gas fired block is being built near Fredericia in Jutland.

Biomass presently contributes somewhat to the heat production but only on a more limited scale to the electricity production. However, as biomass is essentially CO_2 neutral, substituting coal with biomass is seen as an effective mean to meet the national CO_2 policy. Thus several biomass to electricity projects, including some large-scale plants are emerging.

Due to good (substituted) project economy there is also a growing contribution from wind power for which the installed capacity is now approx. 600 MW_e (Elsam posten No 1,1996). In fact, the relative size of especially wind electricity is becoming problematic to the utility sector, which is caused partly by the unpredictability of the production and partly by the lack of central control of the large privately owned part of the production capacity.

Solar energy is politically and economically encouraged for house heating but the production is still nearly statistically invisible. Photovoltaic energy has neither been implemented to a significant extent nor is it expected to be so within the next 5 to 10 years.

All in all, renewable energy contributes 63 PJ/year or some 8 % of the total Danish consumption of primary energy including the transport sector (see, e.g., Handlingsplan for vedvarende energi 1995-97).

1.1.2. Biomass sources and use

From Mosbech, 1994 it can be seen that the total quantity of biomass available for energy production in Denmark corresponds to be approx. 115 PJ and that approx. 40 % of this potential is actually utilised.

Hence, around 6 % of the gross energy consumption is covered by use of biomass (including municipal waste incineration). This utilisation has mostly been for heating purposes using a large number of small wood-/straw-fired individual or farm ovens as well as more than 100 district heating plants, which are typically sized several MW_{th}. However, the tendency is towards including electricity production wherever possible. Therefore, all major waste incineration plants as well as around ten fully or partly wood- and/or straw-fired CHP plants exist in the size range 2 to 20 MWe.

Besides, some new medium- and large-scale biomass to electricity projects are actually realised or investigated by the power utilities. However, all of the most actual projects are based on various combustion technologies and not on gasification.

In the scale slightly above 1 MW_e the Danish company Vølund aims at running an engine on gas from updraft wood gasification in 1997. Besides a few activities are going on in the sub-MW_e range. More specifically these activities concerns the demonstration of a French down draft gasification -IC-engine process and some R,D&D work with some other processes developed in Denmark (see section 3.1 and 4.1).

The types of biomass considered most relevant to energy production in Denmark are:

Residue products:
- Municipal waste
- Straw
- Wood (round, forestry waste, industrial waste and demolition)
- Animal manure
- Organic waste from slaughterhouses etc.
- Landfilled waste (for gas production)
- Sewage sludge (digestion, and thermal conversion)

Energy crops:
- Whole cereal plants and grain alone
- Wood from short rotation forestry (SRF)
- Mischanthus
- Rape oil (Raw or as RME / biodiesel)
- Various other crops usable for ethanol production

Figure 1 shows the relative distribution between the various renewable energy sources that adds up to the previously mentioned 63 PJ.

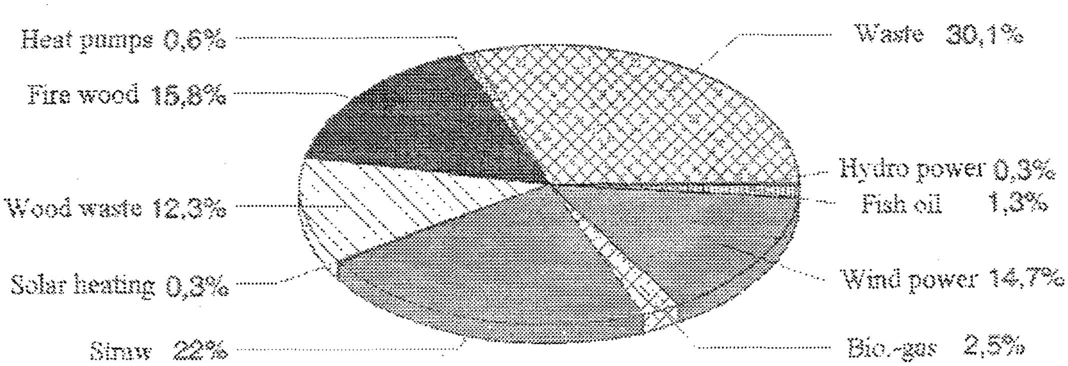

Figure 1. Consumption of renewable energy in Denmark - recalculated to fuel equivalents ("Energistatistik 1993")

The figure is based on the Danish "Energistatistik 1993" and has been reproduced from "Handlingsplan for vedvarende energi 1995-97", which is a recent action plan prepared for the Danish Energy Agency.

Within the group named "residue products" municipal waste, which amounts to 30.1 %, is the largest contributor to the renewable energy sources. There is capacity for incinerating municipal waste to an extent where more than 75 % of the combustible types of household- and ordinary industrial waste production is handled. Generally, these plant produces district heat, but now all except the smallest ones have been or will be converted to producing electricity as well. Hence there are at least 12 Danish CHP plants that use municipal waste.

Straw is next with a share of 22 % of renewable energy sources. There is some uncertainty as to the amount of present resources available for energy production, but around 2.5 million tons are believed to be available in an average year. Less than half of this potential is actually utilised. Unfortunately however, the figure for an average year covers great variations and, for instance it is feared that it will quite frequently be a problem for the power utility sector to rely on the presence of the yearly 1.2 million tons that they have agreed to use for electricity production before the year 2000. A further limiting impact on available straw resources may be from industrial use (e.g. production of cellulose) and from a more ecologically compliant farming sector using more straw within their own production.

Fire wood (which should essentially be the same as round wood) contributes with 15.8 % of renewable energy sources and wood waste with further 12.3 %, i.e. these two categories together contributes with nearly as much as municipal waste and with slightly more than straw.

The power utilities have also agreed to use 200.000 tons of wood for electricity production by the year 2000. This part (which amounts to 15 to 20 % of the wood consumption for energy purposes) is considered much less problematic than straw due to less difficult combustion characteristics and due to the prospects of a stable long-term supply.

Digestion gas produced from animal manure and other types of organic material contributes with only 2.5 % of the renewable energy sources. According to Mosbech, 1994 the resources are much higher and therefore, the contribution may be raised from 2 to 27 PJ/year.

When the number of digestion gas plants was summed up at the end of 1994, 15 were on animal manure, six on gas from waste disposal sites and 110 on anaerobe digestion of sewage sludge (Handlingsplan for vedvarende energi 1995-97). In a number of cases, electricity is produced on IC-engines using the methane rich gas.

The organic matter prevailing a potential sewage sludge digestion process is not included in the above statistics, but the yearly production of such sludge is in the order of several hundred thousand tons on dry basis. The major part has been used as soil improving material, i.e. it has been spread on farming land. This, however, is seen as more and more problematic due to the potentially polluting content of ecologically foreign components such as dioxins. Actually, many farmers consider stopping receiving the sludge. Technologies exist for incineration of mechanically and potentially thermally dewatered sludge, and some of them offer net energy and even some electricity production. However, the general experience is that incineration of the residual sewage sludge is energy consuming. Fossil fuel, e.g. is used in auxiliary burners when mechanically dewatered sludge is co-fired in waste incineration plants.

Energy crops are at present not a significant contributor and for that reason small actual productions are mostly related to experimental activities. Mainly due to the European actions that released large farming areas for (subsidised) non-food production and to the doubts about stable long-term availability of straw, the contribution is expected to increase considerably in the years to come. As mentioned by Mosbech, 1994 however, the gain in total biomass resources may be low because biomass waste products were previously produced from the same land.

Whole plant cereal crops have been used at the usually straw-fired CHP plant in Rudkøbing and the option of using grain alone for energy production is also pursued. Hence, especially because grain is very easy to handle, burning grain is seen as a practical solution for plants that are too small to include economically the preparation equipment needed for other more troublesome types of biomass.

An attempt at production of biomass fuel by short rotation forestry (willow) was expected for the first time in MW scale in connection with the now cancelled 7 MW_e / 8 MJ/s "biocycle" project that was supported by the THERMIE programme. In addition a Danish company named "Agrobrændsel DK A.m.b.a." has been formed; it gathers some 40 Danish farmers that have started a production of willow on their fields. However the scale is still small and on an experimental basis such as the growing of 20 different species on 20 hectares in Northern Jutland (ELSAM posten no 10, 1995).

Rape oil may be used directly or for the production of RME, i.e. as fuel for more or less modified diesel engines. As practised in many countries various other biomass products may be utilised through digestion for producing ethanol and may in this way serve as a substitute for gasoline. There is some focus on these opportunities in Denmark but contributions are still statistically invisible.

1.2. Norway

1.2.1. Primary energy consumption

The total annual Norwegian energy consumption amounts to approx. 1000 PJ or some 25% more than the Danish consumption.

As is the case in Denmark, Norway has not implemented nuclear energy but hydropower is playing a very important role. In addition Norway discovered and started to utilise its (also much larger) oil and natural gas resources somewhat earlier than Denmark. Thus, large-scale electricity production based on coal and other solid fuels has not been extensively pursued as in Denmark.

1.2.2. Biomass sources and use

Biomass covers approx. 36 PJ or 3.6 % of the Norwegian energy consumption (Risnes, 1995).

Around half of it is used for private households heating and slightly less by the industry. The "technical biomass fuel potential" is estimated to be as much as 14 times larger than the actual use. However, a technical potential here means a maximum without considering the costs. As a more realistic future potential the ref.: "Programbeskrivelse ..., 1993" deals with the amounts of renewable energy that are expected to be exploitable within a maximum production cost of 0.50 NOK/kWh. Such defined economic bioenergy resources are estimated to be capable of contributing with approx. 70 PJ/year. This may be compared with correspondingly estimated economical resources of approx. 20 PJ/year from wind power, approx. 15 PJ/year from solar energy and more than 900 PJ/year from hydropower.

Due to the fact that more than 20 % of the Norwegian area is forest, the major biomass source is wood products from forestry and residuals from wood processing industries. The main energy use is as fuel in a large number of wood-fired ovens for individual house warming. Furthermore, woody fuels are used in small district heating plants or provide process energy within industry.

Straw is estimated to be produced in the order of more than 2.5 million tons/year of which the main part is at present ploughed down as a soil improving agent or burned on the fields. Straw is not utilised for energy production these days but approx. 0.8 million tons/year are estimated to be readily available at production cost of less than 0.50 NOK/kWh.

The major part of approx. 2 Mton/year of the national MSW production is landfilled even though this gives a substantial environmental concern. There are approx. 15 plants without and seven with energy recovery. Only one of these produces electricity (58 GWh/year). In addition, a facility producing RDF pellets supplies a CFB boiler that produces steam in a paper mill (Hustad and Rosvold, 1994). Hence, there is major unused potential for producing electricity both from MSW and from 3.4 Mton/year of other types of waste materials which is available. However, such usually not very effective production would have to compete with the cheap hydropower.

Risnes, (1995) mentions that land fill derived gas is produced from at least four deponies. Furthermore, gas may be produced from digestion of some 350,000 tons/year of sewage sludge, and 11.5 GWh/year of electricity may be produced from such gas.

No SRF projects are known to be established in Norway and due to the large unutilized forest resources such activities will probably not gain importance in the near future.

Eventually it should be noticed that at present there is in Norway no production of electricity based on biomass gasification. However, the Norwegian R&D activities mentioned in section 4.2 may contribute to change this state of things within the years to come.

2. General information on national policies

2.1. Denmark

2.1.1. General

For a number of years Denmark has emphasised the development and implementation of renewable energy. This approach is primarily due to the wish for fulfilling the national environmental goals, which are to bee seen along with the international agreements that Denmark has actively worked for and co-signed. The more recent of these agreements has been summarised by Nielsen, 1995a.

On the international scheme it can clearly be seen that Danish wind mill industry has gained from the generally progressive national R,D&D policy and, similarly, Danish boiler manufacturers now seem to be enjoying the benefits of an early start in developing part of the necessary biomass conversion technology. Hence, Danish technology for producing electricity on biomass combustion has been made commercially available and there is a reasonable hope that various biomass gasification technologies relatively soon being made available as well.

2.1.2. Legislation and driving forces

In general, the national objectives pursued in connection with environmental issues are at the same level as or are more extensive than the commitments pursuant to the relevant international agreements.

Some important legislation and agreements that aims at implementing the present Danish policy in relation to biomass utilisation for energy production are summarised in Table 1. A more detailed presentation has recently been worked out by Nielsen, 1995a,.and further information may be obtained from the references Danish Energy Agency, 1994 and 1995.

It should be noted that the first mentioned item for promoting CHP capacity was not limited to plants for biomass fuels, but due to the geographical distribution of such fuels bioenergy has been promoted also. On the other hand, many of the sites that could provide a heat demand basis for biomass-fired CHP plants are now "occupied" by especially the relatively efficient and low-cost NG-fuelled CHP plants.

Table 1 Danish legislation and agreements that have impact on biomass utilisation.

Action plans/ legislation/ agreements	Time	Main contents
Agreement on decentral CHP	1986	• 450 MW_e decentral CHP capacity that uses domestic fuels to be installed by the power utilities.
Adoption of resolution	1989	• Forest area to be doubled over an 80-100 year period.
Political agreement	20 Marts 1990	• A phased programme within the years 1990-98 that aims at increased CHP production as well as utilisation of NG and other environmentally compliant fuels (formed the framework of the later biomass agreement in June 1993).
"Energy-2000 A Plan of Action for Sustainable Development"	April 1990	• CO_2 emissions from the energy sector must be reduced by 20 % from its 1988 level by the year 2005 • SO_2 and NO_x emissions must be reduced by 60 and 50 %, respectively, within the same period.
Law on heat supply	13 June 1990	• Gives the Minister of Energy the power to regulate the choice of fuel for central, CHP and district heating plants
Law against straw burning in the fields	1991	• Straw burning in the fields is prohibited
EC initiatives concerning fallow fields	1992	• Made 15% of farmland available for (subsidised) non food production.
CO_2 laws	1992	• Subsidies for promoting CHP plants and biomass fuels. • Subsidies for electricity production. • Subsidies for completion of distribution nets for district heating.
Biomass Agreement	14 June 1993	• At least 1.2 million tons/year of straw and 0.2 million tons/year of wood to be utilised by the utility sector for electricity production before the year 2000. • 11 cities with access to NG but that have not yet converted to NG-fired CHP are allowed to choose biofuelled CHP instead and in that case they may await improved technology until the year 2000. • Some district heating plants without access to NG must be converted to biofuels before the year 1996 or before 1998 if they have been converted to CHP production. • 6 district heating plants presently based on biomass fuels must convert to bio-CHP before year 2000. • Some further 60 district heating plants must at the latest in 1998 convert to biomass, extend their distribution nets and, possibly, also convert to CHP.
Energy 2000 follow-ups	Autumn 1993	• A number of further initiatives and means for implementation were presented by the government as a follow up to "Energy 2000". • Conversion from district heat to CHP production and/or substituting coal and oil with NG and biomass (including waste) is emphasised for various specific plant categories.
Further / recent action plans on:		• Renewable energy. • Waste and recycling. • Clean technology.

According to the action plan "Energy 2000", the reductions in CO_2 and other emissions are to be achieved through actions mainly within the following four main areas:

- savings in energy consumption;
- conversion of the supply system and higher efficiency by, for instance, co-production of heat and power;
- increase the use of cleaner sources of energy;
- R&D activities.

Cleaner sources of energy in this case include renewable sources and natural gas. Compared with the 1988 figures, the goals for the year 2005 with respect to energy and fuel consumption are:

- reducing total energy consumption by 15%;
- increasing natural gas consumption by 170%;
- increasing renewable energy consumption by 100%;
- reducing coal consumption by 45%;
- reducing oil consumption by 40%.

Along with other types of renewable energy sources, the utilisation of biomass is seen as a quantitatively limited but still important means of reaching the ambitious goals of "Energy 2000". For instance the amount of biomass that according to the "Biomass Agreement" should be utilised by the power companies at the year 2000 corresponds to 19.5 PJ.

A clear tendency towards decreasing CO_2 emission is visible at present. However, due to some initial increase from 1988, the actual rate of reduction is evaluated as being insufficient and there is an ongoing discussion about the way to accelerate the rate of reductions. It is considered how it will be possible also to gain a contribution from the transport sector for which the year 2005 CO_2-emission ambition until now has only been stabilisation at the level of the year 1988.

Not least due to the fact that the power utility sector actively pursues its own biomass action plans, it is doing better and, in particular the western part of the country (the ELSAM area) seems to be fulfilling its part of the goal for the year 2005 already before the year 2000 (Elsam posten no. 1, 1996, p. 2).

The driving forces for efficient biomass utilisation at EU as well as at Danish national and regional levels are the prospects of achieving:

- environmental benefits from CO_2- and SO_2-reductions;
- better utilisation of domestic/local resources and conservation of fossil fuels;
- potential for export of new conversion technologies;
- enhanced local employment, infrastructure and economy.

These are discussed in more detail by Nielsen, 1995b.

Along with a general public concern about environmental issues, the major driving forces for enhanced biomass utilisation at the regional level, and in particular, for the plant owners/investors probably consists of:

- direct instructions from the Danish Energy Agency requesting certain plants to e.g. include electricity production and/or to use certain types of fuel;
- CO_2 taxation on fossil fuels;
- 0.10 DKK/kWh CO_2 -subsidy for using natural gas and biomass fuels;
- 0.17 DKK/kWh subsidy to decentral electricity production of renewable sources;
- economic support from national R&D programmes for specific R,D &D projects.

It should be noticed that for biomass-fuelled CHP plants the kWh subsidies sum up to 0.27 DKK/kWh. One reason why subsidies at this high level are necessary to make biomass an economically interesting fuels option is that compared with coal, biomass is roughly 3 times more expensive on the basis of energy content. In addition, biomass CHP plants are generally less efficient and more expensive to build and operate. In combination with prevailing uncertainties concerning plant availability and the achievement of stable supply of fuel at predictable prices, these are also the main reasons why natural gas fired CHP plants are often preferred in spite of the fact that natural gas is considerably more expensive than coal and in spite of the lower kWh subsidy.

When we look at the driving forces for introducing biomass in large/central power stations only a reduced 0.10 DKK/kWh subsidy is paid. Although the investments are costly, shifting some capacity from coal to biomass fuels is seen as an effective means of meeting the CO_2 emission goal in this sector. Consequently, compared with reductions from using natural gas less than half the amount of (economically superior) coal-based production must be replaced.

Decentral and industrial CHP plants have already been promoted rather successfully. With an estimated capacity of around 1200 MWe the goal of "Energy-2000" for year the 2005 has already been passed. Most of these plants use natural gas, and it is widely held that the 0.10 DKK/kWh subsidy and the previous implementation of a very large and tight natural gas distribution system clearly has narrowed the opportunities for biomass-to-energy projects. Part of the explanation is that the economy of the very investment intensive natural gas transmission and distribution system is strongly dependent on the extent of gas sales. Hence, the opportunities for finding new locations that need district heating capacity on an economically sufficient size are now rather limited and perhaps too small for Danish biomass technology developers to find a adequately large home market.

A more recent governmental policy is that biomass projects have the highest priority whenever the sufficient technology is available but, still, new decentral and industrial natural gas fired plants are gaining footholds on the market due to the relatively low investment costs and the 0.1 DKK/kWh subsidy. In fact, the utility sector is now warning of a situation with large electrical surplus capacity being installed by industrial and private actors. Due to the fact that most of the electricity production timely is close coupled to the demand for district heating, overproduction is a problem. At the present it is mainly in the cold periods of the winter, where also the production from wind mills is high.

It is furthermore a problem that the development time for economic, efficient and reliable biomass technologies has been longer than expected. This means that plant owners that are given a request for e.g., conversion to CHP tend to choose the more commercially established NG-fired options.

Danish R&D efforts to have the necessary biomass technology made available are promoted by national programmes, as mentioned in the following paragraph.

2.1.3. National R&D programmes
The Danish biomass-to-energy R&D activities are to a large extent performed within the co-operation frameworks of the relevant EC-programmes (projects, networks and concerted actions), the IEA co-operation on biomass and on fluidised bed combustion as well as some co-ordinated Scandinavian activities.

In addition more or less purely national activities are going on; typically with participation from the major actors mentioned in section 4.1 which, not least, include the Danish power utilities. In fact, when we look quantitatively at commercial, demonstration and experimental electricity production based on biomass the efforts are mostly pursued by the Danish power utilities.

The two power utility associations ELSAM and ELKRAFT for example both work with the concept of integrating a dedicated biomass boiler into the steam system of large-scale utility boilers. In this way a separate, small, expensive and inefficient steam system is avoided. Furthermore, steam data may be kept at a moderate level in the biomass boiler (reducing the excessive corrosion risks especially from straw). Compared with co-firing the biomass in the main power plant furnace it is also an advantage that coal and biomass ashes are achieved separately.

Such a 110 MW_{th} grate type boiler has in 1995 been ordered by the ELSAM utility I/S Sønderjyllands Højspændingsværk which is located in the southern part of Jutland. In this case steam produced by a straw-fired grate type boiler is further heated in a wood-fired super heater before it is added to the steam system of a large existing pulverised coal-fired boiler.

Somewhat similarly, ELKRAFT has worked out detailed plans for a large new plant named Avedøre 2 where multifuel capability is established by integrating a large (new) natural gas/coal-fired boiler, a biomass boiler and a natural gas-fired gas turbine into the same steam system. This particular system also allows the straw fired boiler to use moderate steam data and, due to the inherent system flexibility, a continuous electricity production is not dependent on a stable and economic supply of neither biomass or natural gas. The overall efficiency will be high due to the use of very advanced steam data in the main system and due to the positive influence from the additional electricity production of the advanced aero derived gas turbine. Emissions will be at the high standard of large-scale power plants.

ELSAM in particular is also looking into the opportunity of achieving the benefits from large-scale plants and securing high plant utilisation through the concept of mixed fired plants. This idea is pursued by working with circulating fluidised bed combustion (CFBC) of coal and biomass. The CFBC concept is considered especially interesting due to the advantage of simplified gas clean-up, inherent fuel flexibility and the possibility of advanced steam data even on corrosive fuels (high temperature superheating may be realised in external particle coolers). Consequently, CFBC is seen as an cost-effective way of establishing flexible and environmentally clean biomass utilisation. Besides some specific technical issues, one problem consists in making proper use of the solid residues produced.

Directly co-firing with biomass in large-scale pulverised coal combustion (PCC) plants is a further major development line. In this case substitution of a small fraction of the coal stream to a large utility boiler is seen as a low cost solution to reach the agreed goals for CO_2 reduction and biomass utilisation. Hence, it is much more favourable simply to provide the equipment for mechanical size degrading and blowing in the biomass than it is to build a separate biomass boiler, especially compared with the need for providing a separate and less efficient steam system.

Due to the risk of corrosion when straw is used and to the interests in separating coal and biomass ashes, ELSAM and ELKRAFT are also looking into more advanced technical solutions to less direct cofiring, i.e. some proper pre-processing of the biomass precedes its input to the utility boiler. If successful, this may create the opportunity for cheap and effective cofiring not only for rather old power plants with moderate steam data but also for new highly effective plants with advanced steam data.

In the MW_e scale ELKRAFT / sk-Energy have realised two straw-fired CHP plants based on dedicated biomass boilers/steam systems (Haslev and Slagelse) and a third one rated 10 MW_e (Masnedø) was commissioned in early 1996. Several ELSAM power utilities work with somewhat similar technology in several small biomass combustion plants. However, the tendency has more been in the direction of direct and/or indirect mix firing, i.e. various combinations of straw, wood chips, waste, natural gas and coal.

All of the above mentioned projects concern biomass combustion, but as mentioned in section 3.1, also a few biomass gasification to electricity projects are conducted, mainly by various industries and local actors.

In addition ELSAM and ELKRAFT as well as European partners have initiated a co-operation on the major biomass IGCC project mentioned in section 3.1.6., but this project is now cancelled in Denmark.

Financing of the relevant Danish R,D&D activities is to a large extent achieved from European, Scandinavian and Danish programmes such as:

- JOULE, THERMIE, ALTENER, APAS and (F)AIR;
- founding through the Nordic Council of Ministers;
- the broad energy research programme "EFP" of the Danish Ministry of Energy, which also promotes, e.g., fossil fuel technology;
- the development programme "UVE" - in particular for promoting renewable energy including biomass.

Both of the national programmes EFP and UVE are administrated by the Danish Energy Agency.

In most cases a request for major industrial cofinancing must be met, and in many cases projects have been made possible through participation and/or economic support from the Danish power utilities. In the future the Danish utilities will probably have to emphasise the more near term activities due to increasing international competition on the electricity market.

2.2. Norway

2.2.1. General

In spite of its great national advantages as to energy supply, i.e. its access to hydropower and its large resources of oil and natural gas, Norway is known as a leading nation in the sense of focusing on global and long-term environmental issues. Norway has consequently very much contributed to accelerate the ongoing discussions about how a long-term sustainable development is ensured. In addition Norway has focused on R&D to promote renewable energy sources which have primarily been defined as bio-, wind.-, solar- and wave energy.

2.2.2. Legislation and Driving Forces

Apart from the incentive from a strongly expressed political interest and a prevalent public concern about environmental issues, this study revealed no specific (e.g. legislative) enforcement of biomass to energy utilisation in Norway.

However, opportunities exist for having national financial support for relevant R&D activities. For this reason, according to Hustad and Sønju, 1992, the yearly budget corresponds to 1.4 million USD (may be compared to 10 million USD in Denmark for the same year).

2.2.3. National R&D programmes

The Norwegian Research Council has pointed out the following R&D items as being important to the future utilisation of biomass (Programbeskrivelse ...,1993), - here in headlines only:

(for near-term)

- domestic utilisation of all kinds of woody biofuel;
- multifuel plants for the production of electricity and heat;
- small wood-fired stoves that offer high efficiency and minimal emissions;
- modular standard landfill gas-fired plants for heat and/or electricity production

(for long-term)

- ecologically optimised exploitation of biomass;
- thermally / chemically / mechanically processing of biomass including solid waste processing.

In particular, two important working areas are identified

- utilisation of secondary products from wood processing industries and waste from all sectors;
- small wood fired stoves with high efficiency and minimal emissions.

In connection with the last item it can be mentioned that some interesting R&D work is carried on at Norges Tekniske Høgskole (NTH) and SINTEF, in Trondheim concerning a novel type of stove based on two-stage combustion.

The Norwegian biomass to energy R&D activities are to a large extent performed within the framework of International Energy Agency (IEA) biomass activities. Hence, as is the case with Denmark, Norway is also a national member of IEA. Furthermore the R&D activities are performed in connection with the relevant EU-programmes and, in addition some co-ordinated Scandinavian activities are undertaken.

3. Commercial and demonstration projects

3.1. Denmark

3.1.1. General

Table 2. gives an overview of all Danish gasification plants. However the following text deals mainly with those which are considered commercial / demonstration plants.

3.1.2. Harboøre

The Danish boiler manufacturer Ansaldo Vølund Energy's research company Ansaldo Vølund R&D in Kolding has conducted R&D work on several biomass technologies including concepts based on biomass gasification. The major and most mature Vølund gasification option is based on an updraft countercurrent gasifier.

Some major advantages of this principle are the possibility of obtaining an energetic gas and high tolerance for fuel moisture (e.g. wood chips containing up to more than 50 % moisture). Therefore a costly and complicated drying system can be avoided, but on the other hand, a moist fuel may decrease the heating value of the raw gas and the cold gas efficiency.

A further advantage is that char conversion may be very high, e.g., 99 %, because of the ash that is usually being almost free from unburned carbon.

The first and presently only (partly) commercial plant is operating at Harboøre, which is located on the west coast of Jutland. For the moment the plant produces only district heat, i.e. the gas is burned and the heat is distributed in a newly constructed district heating system that comprises 550 houses.

At the same time efforts are made to add raw gas cleanup equipment whereby it will be possible to use the gas in an IC engine in order to produce electricity. In this case a major disadvantage until properly solved is the high content of tar in the raw gas. The tar may give severe blocking problems in the downstream system and tar also represent a major loss/disposal problem if it is not converted. Such conversion may be obtained through thermal and/or catalytic cracking. Consequently, condensation/separation and recirculation to the reaction zone is one of the practical solutions pursued, but especially the Danish Technological Institute (DTI) situated Aarhus in Denmark, has pursued a solution based on a monolithic metal oxide catalyst, a process step that is preceded by partial oxidation and a ceramic candle filter.

Table 2. Existing and projected/decided biomass gasification plants in Denmark

PlantName	Location (City)	Owner	Main proces	Type of reactor	Status	Fuel	Gas use	MW th	MW el	Date of comm.	Notes / Features
Aars / Blære Kraftvarmeværk	Blære, Aars	REKA	Pyr & Gasf	MB + DDMB	Demo	Wood (straw)	Engine	0.25 out	0.10	1996	Multi step (0.40 MWin)
Biocycle	Assens / Maribo ?	(ELSAM / ELKRAFT)	Gasf	FB	Demo	Willow, wood	CC	8 out	7.2	Projekt-cansled	Spouted?
COWI / DTU / Pyrol Pilot	Lyngby	DTU, IfE / COWI	Pyrol	HzMB	Pilot	Straw, Wood	(ext. SH)	0.35 in	-	Stand-by	Ext heat
COWI / Vølund / DTU / Pyrol, Haslev	Haslev	sk-Energi	Pyrol	HzMB	Demo	Straw	ext. SH	4 in	?	1996	Ext heat, SH
dk-Teknik open core, bench	Gladsaxe	dk-Teknik	Gasf	Open Core	Bench	Wood chips <20% H2O	R&D	0.21	0.05	1994	Partial low air addition
dk-Teknik open core, pilot	Gladsaxe	dk-Teknik	Gasf	Open Core	Pilot	Wood chips <20% H2O	Engine	0.21	0.05	1995 Autumn	Partial low air addition
DTU IfE, Pyr 2 Bench (x2)	Lyngby	DTU IfE	Pyr	HzMB	Bench	Wood, Straw	Engine	ap-prox. 0.05	-	1995-96	Ext heat, Occil screw
DTU IfE, Two Step 1	Lyngby	DTU IfE	Pyr-gasf	HzMB-DDMB	Bench	Wood, Straw	Engine	0.05	?	1992 - Dismantl	Ext heat add
DTU IfE, Two Step 2	Lyngby	DTU IfE	Pyr-gasf	HzMB-DDMB	Pilot	Wood, Straw	R&D	0.10	?	Commis	Ext heat
DTU IfE, Two Step FB	Lyngby	DTU IfE	Pyr-gasf	FB-FB	Bench	Wood, Straw	R&D	0.025	-	1995-96	Ext heat?, Pygas recl
Harboøre UDMB Gasifier	Harboøre	Vølund	Gasf	UDMB	Comm. / Demo	Wood chips <50% H2O	Engine	4-6 out	1.0-1.2	1997 (Electri-city)	Adv. grid, part.ox
Høgild (Martezo)	Høgild	Heming kom. værker	Gasf	DDMB	Demo	Wood app 20% H_2O	Engine	0.6-0.8 in	0.14	1995 / Commis	
Kyndbyværket UDMB pilot	Kyndby	Vølund / ELKRAFT	Gasf	UDMB	Pilot	Straw (Wood)	R&D	app 1 in	-	1989 Testopr.	
Risø Press. Entrnd Flow Reactor	Roskilde	Risø	Comb / Gasf	EF	Labo-ratory	Coal, Biomass	R&D	-	-	1994	Pressurised
DTI, Aarhus	Aarhus	DTI, Aarhus	Gasf	UDMB	Bench	Wood, Waste	R&D	0.2	-		

The gasifier at Harboøre works on wood chips and the nominal gas production corresponds to a thermal output of 4 MW. However, experience shows that more biomass may be converted in the actual gasifier, but the energy output is restricted by the limited demand for heat. Hence, better opportunities for trying higher loads will arise when it will be possible to produce electricity. The addition of the engine is planned for 1997 and then some 1200 kWe are expected.

Additional specific experience gained from the Harboøre plant is that it is important to obtain a high fuel layer in order to have an upper wet layer that works as a filter in relation to fine char particles and aerosols. Still it has been necessary - and effective - to provide a little partial oxidation at the top of the gasifier in order to minimise blocking problems.

Prior to and in parallel to building and operating the Harboøre plant extensive experimental work has been performed at a similar pilot plant located at the ELKRAFT power plant in Kyndby on Zealand. Part of the experience gained is that wood chips are relatively easy to gasify while straw is much more difficult.

One problem with straw is that the fuel layer gets very thin under anticipated operating conditions and/or reactions easily gets unevenly distributed horizontally. Straw is therefore a very difficult fuel also when it is used in an updraft gasifier. However, some hope for also using straw is partly based on a new type of grate that has now been installed in the Kyndby facility.

3.1.3. Høgild, Herning

This plant is located in a small Jutland town named Høgild near Herning. Høgild's 120 houses/residences recently had a new district heating system. Initially the district heat was supplied by an oil fired boiler but now the heat duty has partly been taken over by the new CHP plant (Aastrup, 1994). The CHP plant is based on a co-current (downdraft) moving bed gasifier delivered by a French producer and comprises a gas engine.

The engine should have been capable of producing 160 kWe, but 135 kWe proved to be a more realistic figure. Before entering the engine the gas is cooled and cleaned in processes that include a wet scrubber, a saw dust filter and a filter type water separator.

The co-current or downdraft principle is ideal for achieving a low content of tar in the gas but, in return, the latent heat of the raw gas is relatively high, which means that the cold gas efficiency is relatively low. The lower heating value of the gas is usually 4.0 - 4.8 MJ/nm3.

Experience also shows that the fuel is limited to large pieces of wood that have a well controlled moisture content close on 20 %. As a result, much attention has to be paid to proper sizing and drying of the fuel, and much manual separation work must be done in this area of the plant. Drying is performed on a belt dryer with hot (district heating) water as the heat source.

In spite of proper fuel preparation, some char coal is coming out of the gasifier along with the ash, and it is relevant to consider reintroducing the char or using it as a fuel somewhere else.

It is reported that poor quality of various hardware items has caused many problems but it is believed that a satisfactory mode of operation will be obtained. The gasifier has during the latest years delivered about 900 hours of electricity production.

The background for the project was a study performed in co-operation between the owner, Herning Kommunale Værker and the Danish Boiler Owners Association dk-TEKNIK.

3.1.4. Blære, Aars

Working with two small pilot experimental facilities the Technical University of Denmark (DTU), Department of Energy Engineering has developed a so-called two-step biomass gasification process, which is now commercially pursued by the Danish company Maskinfabrikken REKA. REKA has built a scaled-up (400 kWth) cogeneration plant at a farm near a small town named Blære which is near Aars in Jutland. During 1995 some primary test work has been performed with wood chips and straw is planned to be used later on. The first electricity was produced in the late part of 1996.

The main principles of the two-step gasification process are illustrated in Figure 2. According to this simplified flow chart, fuel such as wood chips or straw is fed to a first step where pyrolysis takes place at below 600 °C due to the indirect addition of heat. In practice, this step takes the form of a screw conveyer that is heated from the outside, i.e. the exhaust gas from the combustion engine flow along the outer shell surface of the conveyer.

The volatiles produced by the pyrolysis step react with preheated air/steam, i.e. partial oxidation, and consequently, a temperature increase take place. This makes the pyrolysis gas nearly free from tar already before it flows down through the bed of char where it act as a gasification agent.

The gas coming out of the char bed (i.e. the "second step") is cooled and cleaned in a system that comprises a ventury scrubber and, due to the low content of tar, this system can be operated without the problem of, e.g., blocking up as is often seen. The CHP plant in Aars includes a 12 litre Perkins engine rated 100-120 kWe. This engine is expected to match the gas production capacity and, hence, an electrical efficiency of at least 25% is expected.

In the 50 kWth pilot plant at DTU it has been shown that a cold gas efficiency of nearly 90 % can be obtained this way. Furthermore, the overall process is water consuming if the fuel moisture content is below 30 to 35 %, which means that no waste water stream will arise in this case. Test results show a lower heating value of approx. 6 MJ/nm3 (Henriksen, 1994).

At DTU the gas quality has experimentally been proved sufficient for use in small Otto-type spark ignition engines. The first engine used was a naturally aspirated four-cylinder four-stroke FORD (VSG 411) that had a displacement of 1117 cm3 and a compression ratio of 10.5:1. Subsequently a similar but slightly smaller FIAT car engine has been used and in this way some back-firing problems that were experienced at full load with the (rather old) FORD engine have been avoided (Henriksen and Christensen, 1994).

Looking for applications of this interesting process, it should be recognised that heat consumed by the pyrolysis process is added through the wall of the pyrolysing step and, subsequently, the heat has to travel through a layer of preheating/reacting biomass. This means that units above a certain size must be composed of several pyrolysers that work in parallel. Above some relatively small scale (1-3 MWth) this will be a major complication with negative impact on plant economics.

In addition to the plant in Aars a further improved and upscaled experimental plant has been built at the Department of Energy Engineering.

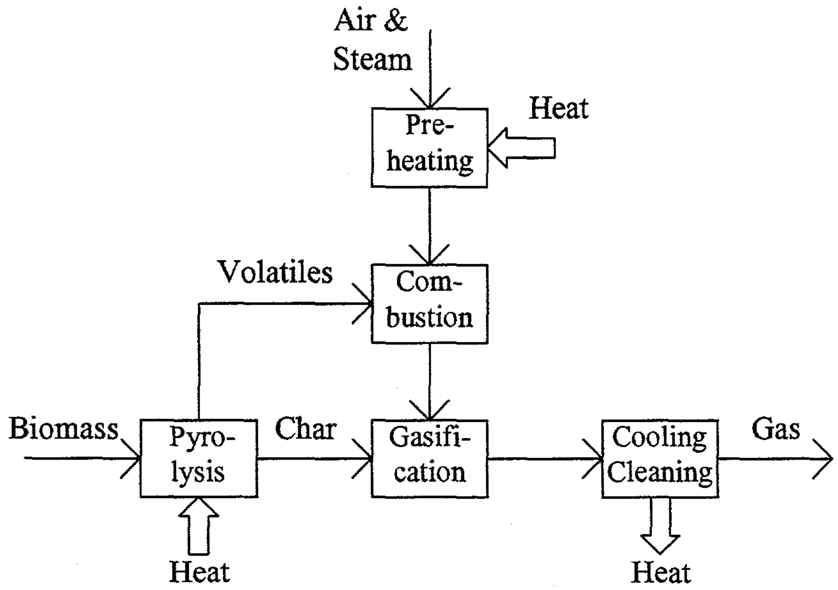

Figure 2. The DTU two step biomass gasification process

3.1.5. Haslev (COWIconsult/Vølund)

In cooperation with Vølund the Danish company COWIconsult has developed a concept for biomass pyrolysis. This is based on some of the findings from the first process step of the DTU two-step gasifier described above. A somewhat simplified system comprising such a biomass pyrolysis step in combination with various heat recovering means is seen in Figure 3.

Figure 3

In addition to gaining experience from the small DTU two-step gasification facility, COWIconsult has also achieved experience from operating a relatively large pilot plant that is also located at DTU.

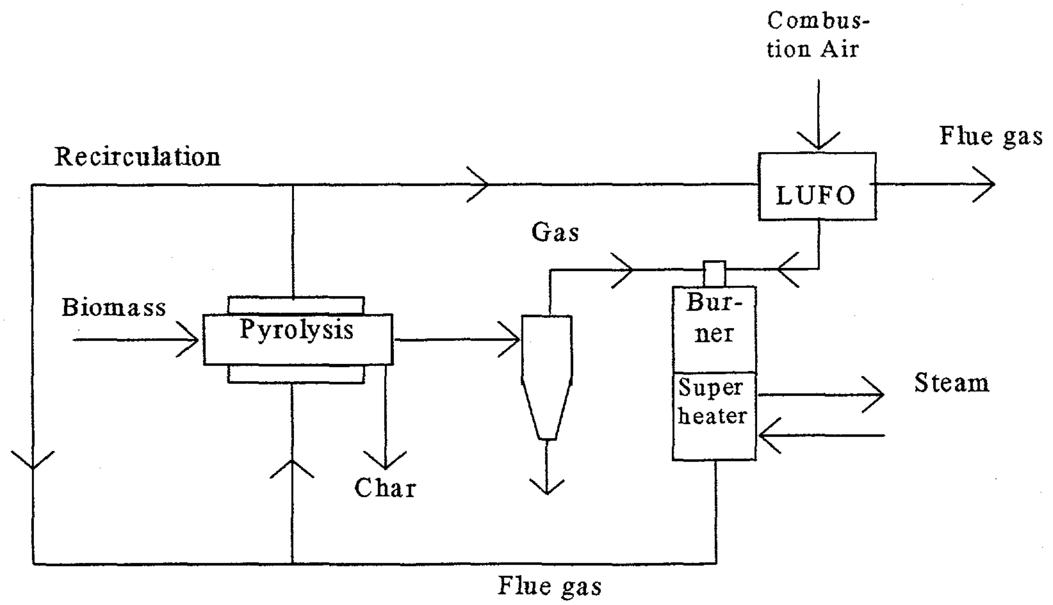

Figure 3. COWIconsult/Vølund concept for external superheating based on biomass pyrolysis

During such a pyrolysis process the temperature can be kept sufficiently low to retain the major part of alkalines and chlorines in the char, i.e., the produced gas is nearly free from these troublesome species. Hence, the gas may be used for further "externally" superheating of the steam produced in biomass or waste incineration boilers and in this way a more efficient steam cycle may be obtained.

In a municipal waste incineration boiler the straw-char containing chlorine (i.e. in a pelletised form) can be burned on the grate along with the waste. Alternatively, the char could be distributed in order to be burned some where else. Looking for application for the char it must be considered that it is enriched with alkalines, chlorine's and ash.

This idea of external superheating by using such biomass derived pyrolysis gas is now being realised in the town Haslev on Zealand in an existing 5 MWe/13 MJ/s straw-fired CHP plant. In this case the full potential of the concept has not been realised, but later when, e.g. the steam pressure is increased along with the superheating temperature 10 to 15 % extra electricity may be produced on the basis of a certain heat demand.

3.1.6. Assens/Maribo (Biocycle)

A project supported by the THERMIE programme and performed by ELSAM and ELKRAFT as the Danish partners have aimed at realising a biomass IGCC demonstration plant rated 7 MWe. Gasification technology supplier was expected to be Enviropower, Finland in cooperation with Vattenfall, Sweden. This concept, which is presented in a strongly simplified form in Figure 4, is probably mostly known from descriptions of the previous (much larger but now cancelled) VEGA project in Sweden.

Some major conceptual characteristics are the use of an air blown pressurised bobbling bed gasifier and hot gas cleanup. According to the usual principles of IGCC plants the cleaned gas is combusted in a gas turbine and high pressure steam is raised in the gas turbine exhaust gases. This is done in order to produce electricity from the combined work performed by the gas turbine and a steam turbine.

One major concern is how to feed the necessary large volumes of biomass against the high pressure of the reaction chamber. At least in the first place a lock-hopper system was proposed, but some efforts were also focusing on the possibility of developing a plug-type feeder.

The anticipated types of biomass were waste wood and willow. Waste wood would be dominating from the start but the idea was that willow should constitute some 80 % of the fuel when willow delivery from large-scale short rotation forestry became sufficient.

The location for the plant was not decided but a location near the cities of Assens or Maribo were considered. Calling for bids should have taken place in the middle of 1996 (Madsen, 1995-96). However, it seems now that this project will not be realised in Denmark.

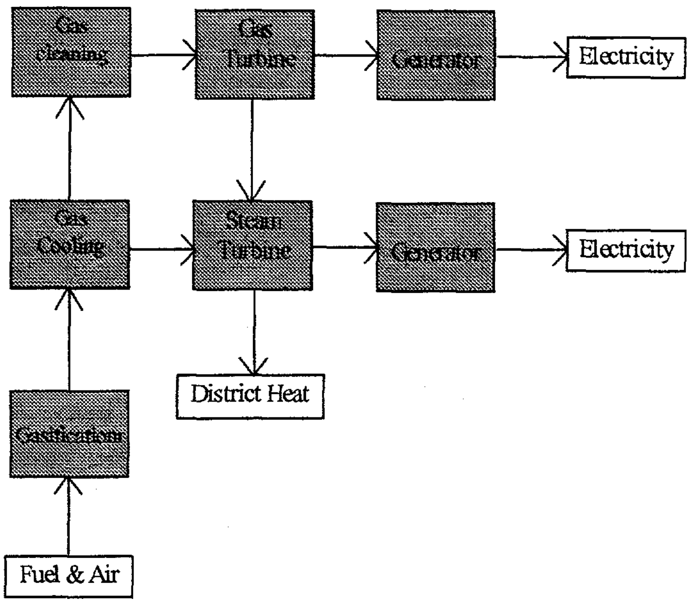

Figure 4. Simplified representation of the IGCC process

3.2. Norway

There are no existing plants or actual Norwegian projects that aim at electricity production based on biomass gasification but, as mentioned in section 4.2., there are some relevant R&D activities.

4. R&D activities

4.1. Denmark

4.1.1. General

In addition to the R&D activities pursued by the producers of technology, several public research-, educational- and other institutes perform R&D activities that relate to electricity production based on biomass gasification. Short presentations of the major participants are given below.

4.1.2. ELSAM/ELKRAFT

Even though they do not have experimental R&D departments of their own, experts from the power utility associations ELSAM and ELKRAFT participate in many national and international activities relevant to electricity production based on biomass gasification.

In particular, they conducted the recently concluded APAS project "Gasification of Coal and Biomass" which comprised extensive pressurised straw and coal gasification experiments at NOELL in Germany, VTT and Enviropower in Finland as well as Risø in Denmark. Some gasification tests in relation to the "biocycle" project mentioned in section 3.1.6 were performed with willow at the pressurised Enviropower test facility in Finland.

4.1.3. DTU (Danish Technical University)

Two departments at DTU (located in Lyngby near Copenhagen) work with subjects related to electricity production based on biomass gasification.

The Department of Energy Engineering has contributed to several new small scale biomass concepts. Hence, some of the most relevant activities are:

- R&D work related to the so-called "two-step process", which has been adopted by the Danish company Maskinfabrikken REKA (see section 3.1.4).
- Pursuance of a concept based on biomass pyrolysis for producing gas that is nearly free from chlorine (in co-operation with the Danish companies COWIconsult and Vølund). The reactor is similar to the first stage of the above mentioned two-step process.
- More basic activities directed at gasification such as macro-TGA experiments in connection with the work on fixed bed technology.
- Some recent and ongoing activities into a new fluid bed based two-step biomass gasification process (Houmøller et al., 1995).

At the Institute for Chemistry, the CHEC-programme is known for its contribution within subjects that have been related to coal combustion but of which many are also relevant to biomass gasification.

High priority is given to obtaining solid understanding as well as experimental and numerical tools for participating in the development and optimisation of plants for thermochemical fuel conversion and related processes for controlling harmful emissions.

4.1.4. dk-Teknik

dk-TEKNIK, which has its headquarter near Copenhagen is actually engaged in several activities relevant to biomass gasification and, e.g., a small experimental open core gasifier has been built (Houmann Jakobsen et al., 1994). The aim is an economically viable concept including an IC engine for producing electricity and heat on wood chips on a small scale.

Additionally, dk-Teknik together with Aalborg Boilers and Risø have been looking into the feasibility of gasifying straw in a circulating fluidised bed (Stenholm Andersen et al., 1989). dk-TEKNIK has also participated in the co-current gasification demonstration project in Herning.

dk-Teknik participates also in the above mentioned activities at the Technical University of Denmark relating to the new two-stage FB based biomass gasifier.

4.1.5. DTI (Danish Technological Institute) and Centre of Biomass Technology

The Danish Technological Institute (DTI) which is partly located in Taastrup (west of Copenhagen) and partly in Aarhus in Jutland are known for the following activities:

- Housing and partly constituting The Centre of Biomass Technology that among other things contributes to the transfer of know-, how and expertise to new biomass projects (see, e.g., Nikolaisen et al., 1992; Suadicani et al., 1993).
- Testing of and assisting in the development of small-scale biomass boilers.
- Working together with Vølund on the Vølund up-draft gasifier.
- Development of updraft gasification of contaminated waste.

- In particular the part of DTI located in Aarhus is addressing the severe tar problems that are presently a major obstacle to integrating an IC engine in the Vølund biomass gasification plant in Harboøre (see section 3.1).

4.1.6. TKE (Thomas Koch Energi)

TKE is a privately owned company located in the small town Gadstrup near Roskilde at Zealand. Its main activities relate to various biomass technologies including biomass logistics, preparation, drying, de-watering, atmospheric and pressure feeding and combustion, / gasification.

Priority is given to contributing with new innovative solutions but also some state-of-the-art reports and feasibility studies have been worked out.

4.1.7. Risø (Risø National Laboratory)

In addition to participating in various projects that broadly aim at the exchange of "biomass" experience (such as the present project), Risø has been engaged in a number of relevant activities:

- A literature survey that addresses the gasification of straw (Jørgensen, 1989; Stenholm et al., 1989); conducted in co-operation with Aalborg Boilers and dk-Teknik.
- Mathematical modelling of fixed-bed and fluid bed gasification of biomass (Kirkegaard et al., 1989).
- Various activities aiming at the development of a biomass fuelled slagging cyclone gasifier, to be used in a system with an externally fired gas turbine, in co-operation with Vølund R&D.
- The large recently concluded APAS supported project named "Gasification of coal and biomass" conducted by the Danish power utilities ELSAM and ELKRAFT. Besides extensive work for retrieving reaction kinetic data using a Pressurised Termo Gravimetric Analyser (PTGA) and a Pressurised Entrained Flow Reactor (PEFR), Risø participated with some experiments using image processing for size characterisation of straw and with a literature survey on large-scale plant concepts based on biomass gasification.

According to the overall Risø strategy the activities have lately been concentrated on strategic and more fundamental research. An extensive set of reactivity data is, e.g., being generated for coal and biomass reacting under atmospheric as well as pressurised conditions. In both case's experiments that represent pyrolysis, combustion and gasification conditions have been performed.

Unfortunately, the change in strategy has consumed many resources and also due to the external interest mainly in short term development work the Department of combustion Research was closed at the end of 1995. However, some of the research activities have been transferred to two other Risø departments, i.e., the Optics and Fluid Dynamics Department and the Plant Biology and Biogeochemistry Department.

4.2. Norway

4.2.1. NTH / SINTEF

NTH / SINTEF are the main Norwegian research institutes within combustion and related areas and, hence, these institutions conduct various activities in relation to the energetic utilisation of biomass.

One activity, that has recently been introduced, relates also to electricity production based on biomass gasification. In this case the aim is to look at the problems and opportunities for mixing a minor part of, e.g., biomass derived gas with natural gas. At first a gas simulating such a mixture is to be burned in an experimental burner but it is contemplated to study the use of an IC-engine in this context (Husstad, 1995).

4.2.2. Kværner Engineering a.s.

Kværner Engineering a.s. is developing a gasification system that is capable of producing electricity from biomass and waste fuels.

The gas is produced in a countercurrent updraft gasifier that may be blown with air, oxygen enriched air or pure (for example 85 %) oxygen. Slagging conditions are maintained in the lower part of the reaction chamber by preheating the gasification agent (air/oxygen) while utilising some of the raw gas enthalpy. A part of the raw gas enthalpy may be used for raising steam.

One main characteristic is adding to the raw gas a small high velocity (400-600 m/s) stream of air that -using a small amount of electricity- is brought into the temperature range of a plasma. Due to the energy content of the plasma stream and due to the partial oxidation that takes place, the raw gas temperature is raised to some 1100 °C in a post-reaction chamber located immediately downstream the gasifier. In this way a raw gas that is almost free from tar is obtained.

The main system including a material and energy flow example for 2.2 t/h of biomass and using air as gasification agent is shown in Figure 5

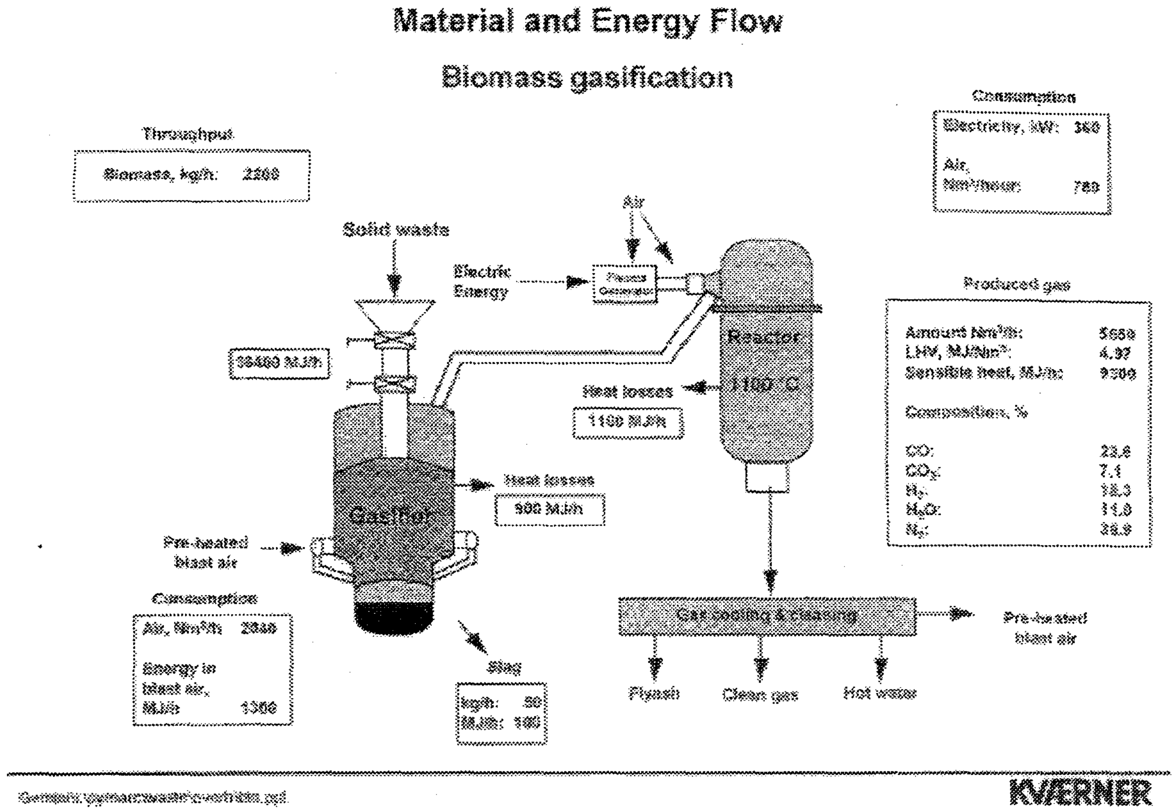

Figure 5. "Pyroarc" biomass gasification system

The proportions of the energy flow are illustrated on the corresponding Sankey diagram in Figure 6.

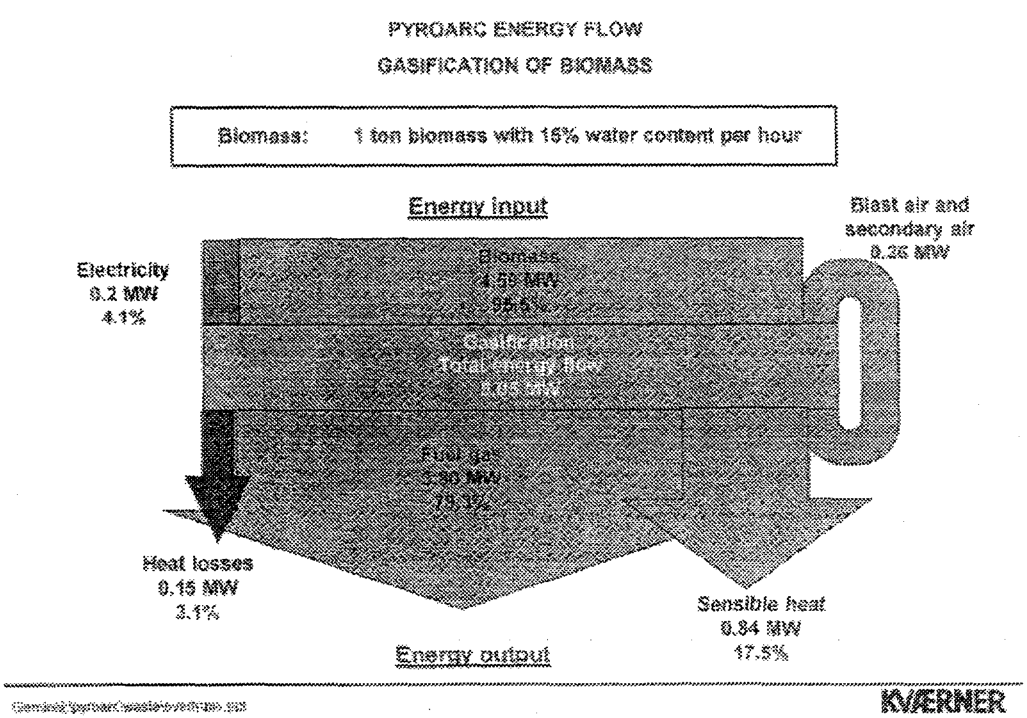

Figure 6. Energy flow in Pyroarc gasifier - example for biomass.

The gas composition presented in Figure 5 illustrates that the aim of achieving a high share of the light combustible components CO and H_2 have been fulfilled. Therefore, the plasma reactor is seen as an effective solution to the severe tar problems usually experienced when countercurrent gasifiers are used. The other common problem of high sensitivity to the fuel particle size distribution may be counteracted by adding a fraction of fines through the air/oxygen nozzles of the gasifier that is pneumatically entrained in the gasification agent (Lynum,1996).

4.2.3. Ulstein Bergen

Ulstein Bergen, located in Bergen, is a Norwegian producer of medium speed spark ignited IC engines.

The gas engine concept is characterised by the addition of fuel gas through mechanical gas valves located in the wall of the inlet manifold just outside two main inlet valves to each of the cylinders. This concept provides good opportunities for using syn-gases that contain hydrogen. Hence, the tendency for back-burning is easier dealt with when the inlet manifold and a potential turbocharger are not filled with gas. Back-burning into the gas supply tubes may be prevented by not opening both of the two serial valves simultaneously. This type of engine has been used for city gas containing approx. 50 % hydrogen.

A further characteristic is that the gas flows to a pre-combustion chamber that permits the engine to work at lean combustion conditions (λ = approx. 2) and, consequently, low emissions can be achieved.

This engine concept works well on high heating value types of gas such as gas consisting mostly of methane. In Denmark for example a relatively large natural gas-fired CHP plant has been built in Brønderslev in Jutland (seven Ulstein Bergen engines supplying 22 MW_e / 26MW_{th}). One smaller plant using gas derived from the digestion of mainly agricultural waste is located in Lemvig, also in Jutland.

The engines in question are supercharged and due to inlet pressure losses through the control and inlet valves as well as through the pre-combustion chamber the gas must be provided at a pressure of at least 2.5 - 3 barg and some 4 bar when going to gas at 16 MJ/kg (e.g. landfill gas containing only 48 % of CH_4). Lower heating value gas is expected to be technically possible and, therefore in some unrealised projects Ulstein Bergen has been looking into using pyrolysis gas at approx. 10 MJ/Nm3. Even lower heating values may be possible but capital costs increase significantly due to decreasing volume specific power yield (Skarbø, 1995; Frederiksen, 1996).

5. Economy

Table 3 shows efficiency, investment as well as operation and maintenance (O&M) data for different biomass to electricity options. Four combustion technologies are included for comparison. The figures are for the year 1993 with the expected figures for year 2005 (in brackets) and have been collected as best estimates from a number of different Danish actors. It should be noticed that the Danish Energy Council, have set some rules for giving the estimates, but data cannot be expected to be mutually comparable and, in particular, they are not earlier brought together as close as done in this report.

It can be seen that the two large-scale mixed fired and add-on combustion options (rows 3 and 4) seam very compatible among the options included. Beside this, it is hard to point out some clear winners. Hence, when we look at the estimated investment costs and efficiencies, gasification technologies may be seen as compatible with the somewhat larger stand-alone combustion/steam cycle technologies (two first rows) but this picture becomes uncertain when the high O&M costs for small-scale gasification plants are taken into account. It is considered very important to establish whether it will be possible to design such small-scale gasification plants in ways that will avoid the need for personnel being present outside normal working hours.

Table 3. Efficiency and economy data for biomass to electricity options (The Danish Energy Council, 1995).

Technology	Type C/G 1)	Fuel	Size MW_e 2)	Efficiency % LHV 3)	Investment MKr/MW_e 4)	O&M in % p.a. 5)	Notes
Small steam boiler and turbine CHP	C	Straw	5-50	23 (24-26)	20-22 (15-20)	5 (4)	
Small steam boiler and turbine CHP	C	Municipal waste	5-20	18-28 (24-28)	30-40 (25-35)	5 (5)	
Large CFB steam boiler and turbine CHP	C	Coal, wood and straw in combination	250	- (45)	- (7.9)	- (4)	6)
Separate biomass boiler producing MP steam to large power plant	C	Straw and wood	100 MJ/s input	-	3.2 Mkr/MJ/s input	2	
Fluidised bed gasifier and gas turbine	G	Biomass, solid waste and coal	2-15	28 (30.5)	25-40 (18-32)	22 (10)	7)
Fixed bed multi-step co-current gasifier and IC-engine	G	Biomass, solid waste and coal	1-3	25 (28)	25-28 (22-24)	25 (10)	7)
Fixed bed counter-current gasifier and IC-engine	G	Biomass, solid waste and coal	1-5	25 (28)	20-23 (18-21)	20 (9)	7)
Large-scale IGCC	G	Coal and biomass in combination	300-400	not available (49)	- -	- -	

Notes:
1) C = combustion, G = gasification
2) Net power yield at MCR in CHP mode.
3) Net efficiency value at MCR in CHP mode - based on lower heating value.
4) Excluding interests during construction.
5) In % per annum of investment costs and excluding fuel costs.
6) Data for pure condensing operation (no heat production).
7) Source relates scale and investment, - O&M is for 1 MW multi step and 5 MW counter current gasifiers

Therefore, from Danish and Norwegian experience it is not possible to give reliable economy data on the options for converting biomass to electricity when gasification technology is used. Some data have been published from pilot/demonstration plants/projects but large uncertainties arise from the lack of commercial plants in long-term operation. Furthermore, the effect of a "learning period" is expected to have a major but not very predictable influence (see, e.g., Bridgwater, 1995).

The general expectation in Denmark is that unsubsidised electricity production on biomass will not become competitive with, e.g., natural gas-fired plants at the present fuel costs and certainly not with large-scale PCC plants. This goes for production based on biomass combustion as well as gasification and is due to the fact that biomass technology is normally more expensive in all aspects of cost, i.e., capital, fuel, operation and maintenance costs.

However, three exceptions may exist.

- The use of waste fuels with "negative" costs.
- Biomass combustion and gasification may become a competitive means of achieving a reduced CO_2 emission.
- On very long term, costs relating to fossil fuels must be expected to rise due to the fact that resources are limited. Also on the shorter term - i.e. decades - major changes in fossil fuel costs are possible due to increased demand and political factors influencing the fuel market. The international faith in the nuclear option is on of the more specific major factors.

National and EC level subsidies may of course affect the plant owner's economy to any extent. The national 0.27 DKK/kWh subsidies for de-central CHP plant that uses biomass, e.g., makes combustion plants more or less competitive with natural gas CHP subsidised with 0.1 DKK/kWh. Furthermore, EC subsidies for set-aside (non-food) farmland positively influences the economical feasibility of biomass crops. Especially compared with the major Danish biomass resource straw, biomass crops may also facilitate decisions on economy criteria due to the prospects of more reliable supply and the stabilising effect of fuel prices.

6. Perspectives

Except from those who are responsible for a continued economical supply of electricity and who see some forced extra costs arising from national political demands (beyond the level of demands laid on foreign competitors), the common Danish attitude to bio-electricity is generally positive. The perspectives seen are:

- Long-term supply options on a renewable energy basis.
- Biomass substituting coal is potentially a more economical way of reducing CO_2 emission than substituting coal with natural gas. This is especially the case in the long term, where natural gas resources may run short and become more expensive.

In particular, the option of biomass gasification renders the following perspective possible:

- More efficient and environmentally clean electricity production using advanced technology such as IGCC for medium- and large-scale production and relatively efficient IC engines for small-scale production. In the long term, fuel cells open up for further perspectives and perhaps in all scales (possibly with pipelines from centralised biomass gasification for small-scale CHP production).
- Better opportunities for efficient and environmentally clean electricity production on the inhomogenious and hard to prepare biomass fuels.

- New options for environmentally and energetically better methods of utilising, e.g., municipal waste.

However, in Denmark limiting factors may easily be:

- Shortcomings of the present main resource - i.e. straw - when many farmers increase their own consumption due to more ecological animal production methods.
- The development of alternative biomass uses such as cellulose production from straw.

Both of the above examples bring the growth of energy crops and the use of otherwise inapplicable waste products more into focus.

In spite of the fact that even if it is supplemented with large scale production, i.e., short rotation forestry (SRF), biomass will continue to be a limited resource when compared with gross energy consumption in industrial countries such as Denmark. To gain maximum benefit from biomass therefore necessitates that emphasis is put on increasing efficiency. This route is supported by the known high sensitivity between economic project viability and efficiency. Therefore, some items that should in particular be emphasised in the future are:

- High efficiency IC-engines capable of using low heating value biomass syngas for small scale systems and, perhaps, also Sterling engines.
- Improvement of gasifiers and related systems, i.e., a better chemical conversion as well as a reduction of thermal losses and interfacing irreversibilities).
- Improvement of medium- and large-scale IGCC plant's systems, e.g., improved thermodynamics without introduction of too much complexity for medium-scale use, and more energy efficient methods of feeding low-density and reactive fuels into pressurised gasifiers.
- Indirectly co-firing, e.g., thermal biomass conversion and raw gas cleanup (removing alkalines, chlorine's and ash) together with subsequent addition of the product gas to efficient utility boilers. Hence, if low conversion loss methods can be found, the electricity production efficiency may be improved to the level of modern power plants (47 % net efficiency for coal-fired utility boilers is being realised in Denmark). Furthermore, the prospect of low investment costs and high overall fuel flexibility are present.
- Developing biomass gasification technology that is well suited in combination with fuel cells.

Through some of the routes mentioned above it should be possible roughly to double the efficiency level from the present 20-25 % being common practice for biomass to electricity conversion (as could be seen from Table 3). Figures beyond 50 % and even 55 % for IGCC and/or fuel cell plants are also to be expected in the long run.

High efficiency, good economy and other benefits can in general best be pursued in large-scale plants, but due to logistic factors and other local conditions (including heat demand) small-scale plants will probably continue to draw major attention as well. Consequently, the development of gas IC engines should be emphasised even though the efficiency potential is more limited. Thermodynamics is more favourable for the externally fired Stirling engine, but the stage of development is much lower.

In addition to increasing the efficiency multifuel capability will probably gain strengthened interest. This trend is to allow dimensioning of the biomass utilisation capability according to (at least) the yearly average resources and to ease up implementation by removing the plant owners risk of being forced to buy biomass fuel at periodically high costs. The option of more or less direct co-firing offers good prospect of giving all the benefits of fuel flexibility, efficiency and economy. However, some innovative solutions are needed in order to avoid ash mixing and pursuance of still higher efficiency through advanced operating parameters. Ash separation will probably also gain interest in other types of multifuel plants.

In Norway short-term motives for pursuance of effective electricity production based on biomass gasification will probably continue to be relatively low due to its access to cheap hydropower as well as its large resources of natural gas and oil. In the long run an improved biomass utilisation could contribute to large national and international benefits such as liberating more emission-free hydropower for export. Facilities and logistics for an improved local biomass utilisation may also improve the prospects of, i.e., the shipment of biomass to other countries.

7. References

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